EPA UIC Permit No. R9UIC-CA5-FY13-1

TUBING/CASING ANNULUS PRESSURE EXCURSIONS

An evaluation of the I/W Well 1 expected annular pressure changes was submitted with the February 2015 monthly report to EPA. These calculations, based on the initial 30 days of injection operations, predicted annular pressures to be in the range of 30 – 140 psia. This range was demonstrated to be consistent with thermal effects. Subsequently, annular pressures have been measured outside of this established range (154 – 167 psia). These excursions, reported to EPA Region 9 subsequent to their occurrence, were investigated as a potential loss of mechanical integrity. The investigation found these higher pressures are a result of increased gas injection rates and higher injected gas temperatures. They are consistent with thermal effects and there is no indication of a loss in wellbore mechanical integrity.

The observed variation in the I/W well annulus pressure and temperature since the start of injection operations (February 14, 2015) through March 30, 2015 is shown by **EXHIBIT 1**. The associated injection pressures and rates are given in **EXHIBIT 2**. The annulus pressure began to exceed the expected cyclic range of annulus pressure fluctuations on Friday, March 27, 2015 peaking at 154 psia. The pressure decreased to less than 90 psia before increasing again to 159 psia the next evening. The annulus pressure continued to cycle between 80 and 160 psia during the next two days in sync with the changing annulus temperatures.

In review, the methodology used to predict the change in the annulus pressure is based on the thermal expansion, or contraction, of the confined annular fluid (KCL water). The change in density as a function of the water temperature causes a change in the water volume in the annulus, increasing or decreasing the volume and pressure of the nitrogen cap. The temperature-pressure relationship developed based on the first month of normal injection operations is shown graphically by **EXHIBIT 3.** This relationship was calculated for an initial nitrogen blanket of 0.6 cubic feet at 100 psi on top of 214 barrels of annular fluid.

To investigate the higher pressure excursions, the temperature-pressure relationship for the annulus was extended for water temperature changes greater than +0.25 deg. Celsius. The updated pressure calculations are presented in **EXHIBIT 4A** and graphically by **EXHIBIT 4B**. Higher wellbore temperatures are expected due to increased gas injection rates and higher injected gas temperatures.

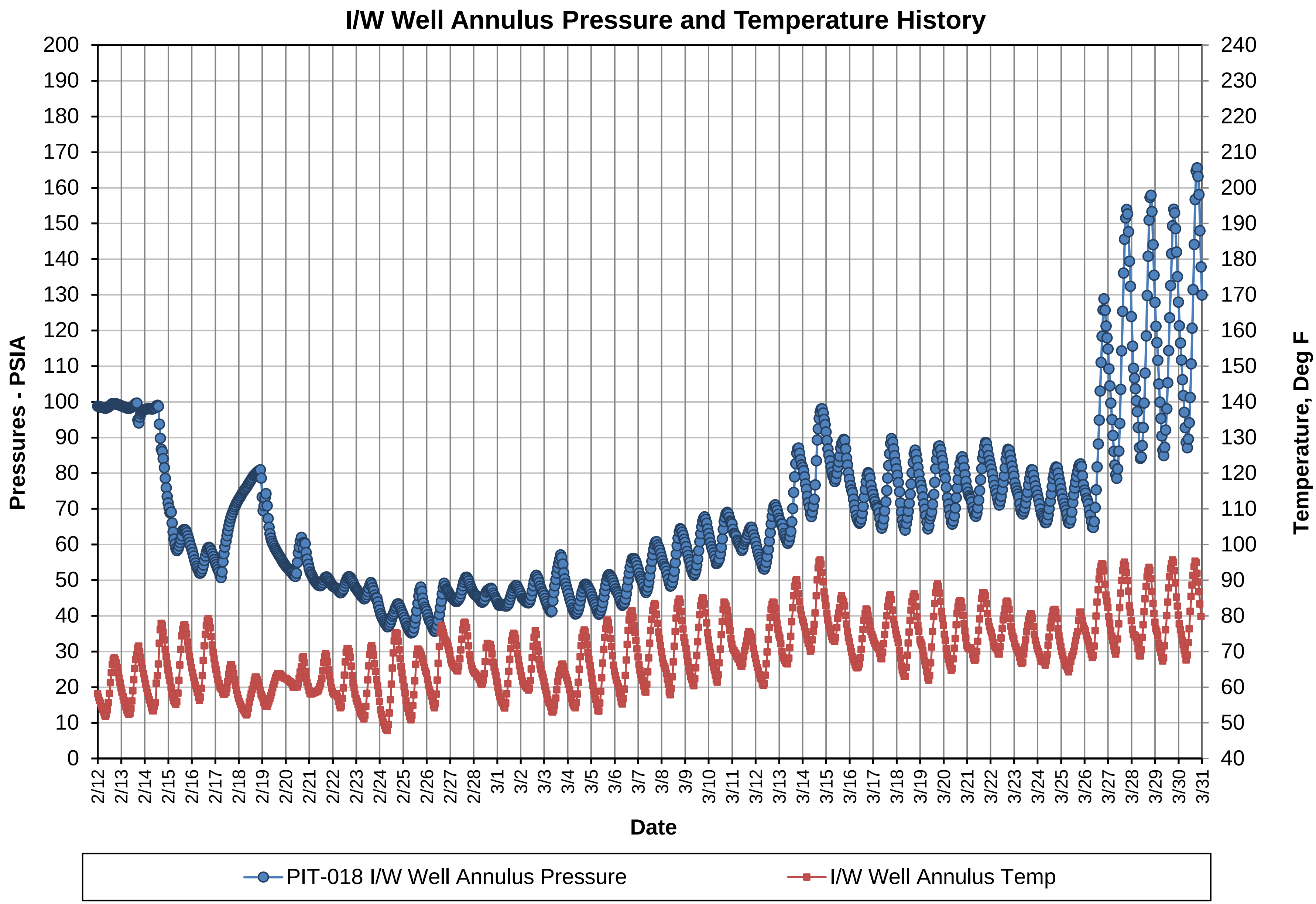
The temperature difference being evaluated in **EXHIBIT 4B** is the difference between an initial T_i and an operating T_f wellbore temperature. The initial average wellbore temperature (T_i) prior to injection is 94.0 deg. F. (average of 60.0 deg. F. surface and 128.0 deg. F. bottomhole). The operating average wellbore temperatures (T_f) are calculated as a simple arithmetic average of the surface wellbore temperature and the bottomhole wellbore temperature. The bottomhole temperature is measured continuously by a surface readout gauge. The surface wellbore temperature, which is not being measured directly, is largely determined as a moving average of the variation in the measured annulus temperatures (less a few degrees for heat losses). The temperature profiles are presented by **EXHIBIT 5**.

Based on the first month of injection operations, the pressure-relationship was only evaluated for water temperature changes between 0.0 and -4.0 deg. Celsius (**EXHIBIT 5**). However, the recent pressure excursions above 140 psia have occurred as a result of annulus water temperature changes greater than 0.50 deg. Celsius.

The extended pressure-temperature relationship shows that the annulus pressure begins to increase exponentially for changes in water temperature greater than +0.25 degree Celsius. This explains the larger excursions in annulus pressures since Friday March 27 because the annulus temperatures have increased due to the higher injection rates and temperatures. Using the extended pressure-temperature relationship, the annulus pressures are calculated and compared to the observed annulus pressures (through March 30) in **EXHIBIT 6**. There is reasonable agreement between the calculated and observed pressures for the range of water temperature changes investigated. Based on these results, it is concluded that the observed I/W well annulus pressures to-date can be attributed to thermal effects and not to any wellbore integrity issues. This is reinforced by the fact that the annulus temperatures and air injection temperatures are cycling in sync with the annulus pressures.

REVISED RANGE OF ANNULAR PRESSURES

The revised expected cyclic range of I/W well annulus pressure fluctuations during injection operations is 30 – 600 psia. The upper range in annulus pressure is calculated for an average annulus water temperature (T_f) of 97.6 deg. F compared to the initial temperature of 94.0 deg. F. (delta temperature of +2.00 deg. Celsius on **EXHIBIT 4B**). An annulus pressure measured outside of this pressure range (especially if the pressure fluctuation does not coincide with the annulus temperature fluctuation) may indicate a potential loss of mechanical integrity and will be reported to the EPA and reviewed by PG&E.



I/W Well Annulus Pressure and Temperature History
Pressures - PSIA
Temperature, Deg F
Date
0
10
20
30
40
50
60
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90
100
110
120
130
140
150
160
170
180
190
200
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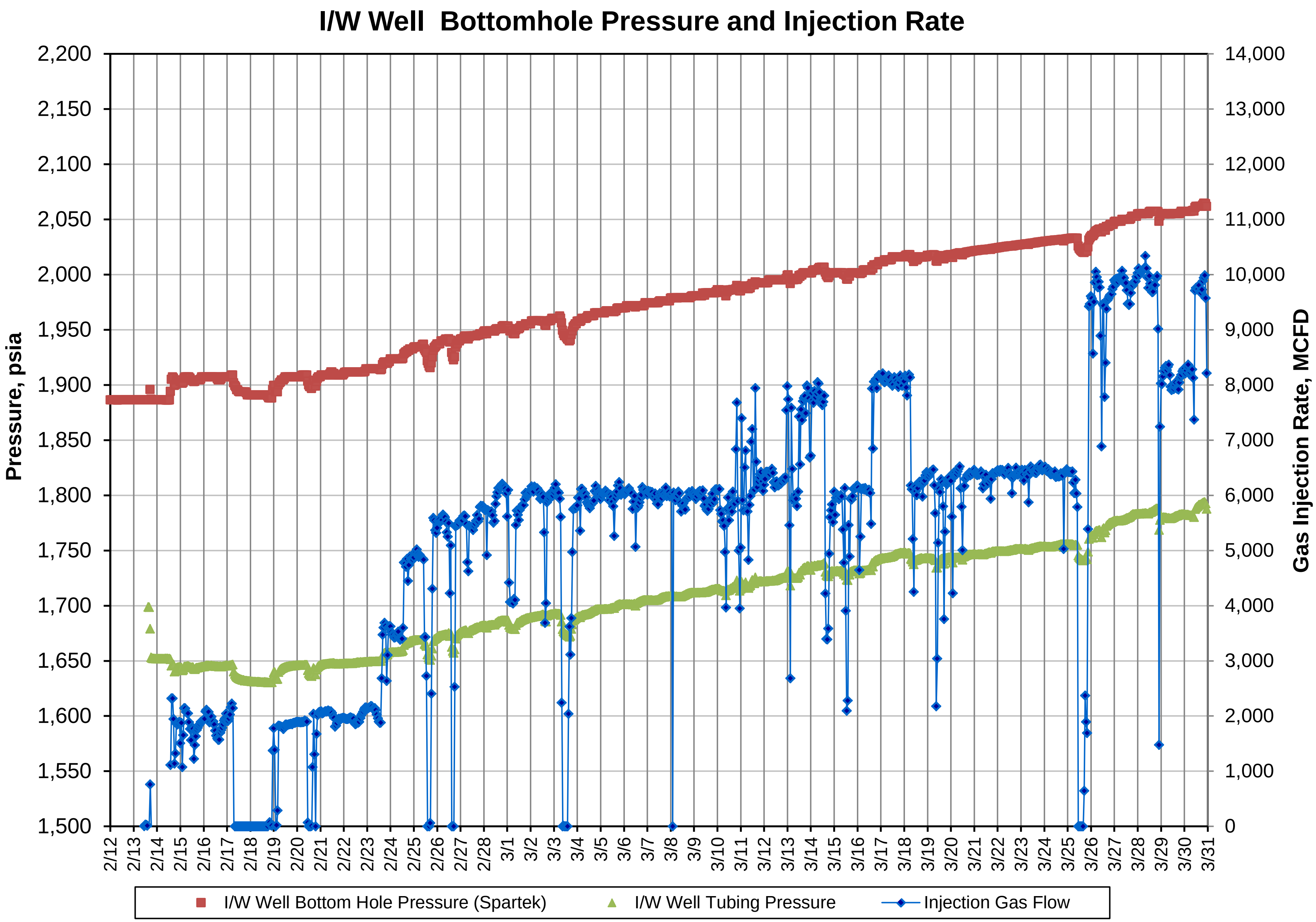
PIT-018 I/W Well Annulus Pressure
I/W Well Annulus Temp


I/W Well Bottomhole Pressure and Injection Rate
Pressure, psia
Gas Injection Rate, MCFD
2,200
2,150
2,100
2,050
2,000
1,950
1,900
1,850
1,800
1,750
1,700
1,650
1,600
1,550
1,500
14,000
13,000
12,000
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
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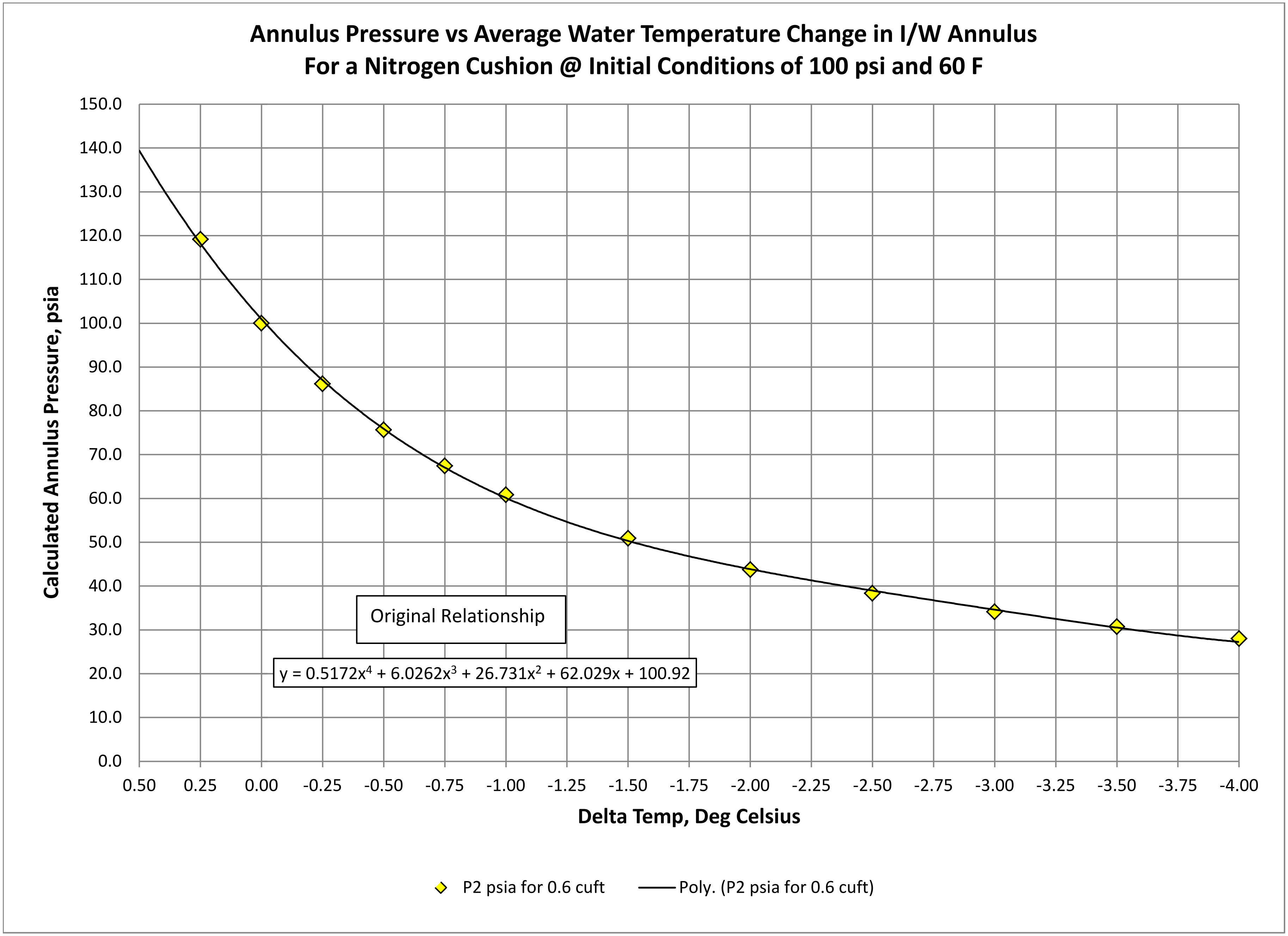
I/W Well Bottom Hole Pressure (Spartek)
I/W Well Tubing Pressure
Injection Gas Flow


Annulus Pressure vs Average Water Temperature Change in I/W Annulus
For a Nitrogen Cushion @ Initial Conditions of 100 psi and 60 F
Calculated Annulus Pressure, psia
150.0
140.0
130.0
120.0
110.0
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
0.50
0.25
0.00
-0.25
-0.50
-0.75
-1.00
-1.25
-1.50
-1.75
-2.00
-2.25
-2.50
-2.75
-3.00
-3.25
-3.50
-3.75
-4.00
Delta Temp, Deg Celsius
Original Relationship
$y = 0.5172x^4 + 6.0262x^3 + 26.731x^2 + 62.029x + 100.92$
P2 psia for 0.6 cuft
Poly. (P2 psia for 0.6 cuft)

I/W Test Well Annulus Pressure Calculations based on the change in Water Density as a Function of Temperature

ASSUMPTIONS & INPUT PARAMETERS

Annular space between 9-5/8" 40# and 5-1/2" 17# pipe =	0.2607	cuft/ft
Length of annular space (packer @ 4614' MD) =	4,614.0	ft
Total annular space =	1,202.9	$feet^3$
Total annular space =	214.2	barrels
Estimated initial wellhead volume available for N2 =	0.80	cuft
P1 = Initial pressure of N2 =	100.0	psia
T1 & T2 = temperature of N2 =	60.0	F
z factor for N2 @ 100 psi and 60 deg F =	0.995	
No of moles N2 =[100 psia x N2 cuft]/[0.995 x 10.732 x (460+60)] =	0.0144	moles

Volumetric Temperature Coefficient of Water, β (www.engineering toolbox.com)

Deg C	Deg F	β, m3/m3 deg C
10.0	50.0	0.000088
20.0	68.0	0.000207
30.0	86.0	0.000303
32.2	90.0	0.000321
40.0	104.0	0.000385

0.000321

P2 = znR(T2)/(V2)

For Plot

delta Temp, deg C	β	delta Vol, m3	Vwi, m3	Vwf, m3	Delta Vol, m3	Delta Vol, cuft	V2, cuft	Calc P2, psia for N2 cap	Original Curve	Extended P2, psia for N2 cap
1.25	0.000321	1.000401	34.0617	34.0753	0.013667	0.482652	0.317348	252.09		252.09
1.00	0.000321	1.000321	34.0617	34.0726	0.010934	0.386121	0.413879	193.29		193.29
0.75	0.000321	1.000241	34.0617	34.0699	0.008200	0.289591	0.510409	156.74		156.74
0.50	0.000321	1.000161	34.0617	34.0671	0.005467	0.193061	0.606939	131.81		131.81
0.25	0.000321	1.000080	34.0617	34.0644	0.002733	0.096530	0.703470	113.72	119.17	113.72
0.00	0.000321	1.000000	34.0617	34.0617	0.000000	0.000000	0.800000	100.00	100.0	100.0
-0.25	0.000321	0.999920	34.0617	34.0589	-0.002733	-0.096530	0.896530	89.2	86.1	89.2
-0.50	0.000321	0.999840	34.0617	34.0562	-0.005467	-0.193061	0.993061	80.6	75.7	80.6
-0.75	0.000321	0.999759	34.0617	34.0535	-0.008200	-0.289591	1.089591	73.4	67.4	73.4
-1.00	0.000321	0.999679	34.0617	34.0507	-0.010934	-0.386121	1.186121	67.4	60.8	67.4
-1.50	0.000321	0.999519	34.0617	34.0453	-0.016401	-0.579182	1.379182	58.0	50.9	58.0
-2.00	0.000321	0.999358	34.0617	34.0398	-0.021868	-0.772242	1.572242	50.9	43.7	50.9
-2.50	0.000321	0.999198	34.0617	34.0343	-0.027334	-0.965303	1.765303	45.3	38.3	45.3
-3.00	0.000321	0.999037	34.0617	34.0289	-0.032801	-1.158364	1.958364	40.9	34.1	40.9
-3.50	0.000321	0.998877	34.0617	34.0234	-0.038268	-1.351424	2.151424	37.2	30.7	37.2
-4.00	0.000321	0.998716	34.0617	34.0179	-0.043735	-1.544485	2.344485	34.1	28.0	34.1
-4.50	0.000321	0.998556	34.0617	34.0125	-0.049202	-1.737545	2.537545	31.5	25.7	31.5

$$V_{wf} = V_{wi} \times [1 + \beta (T_f - T_i)]$$

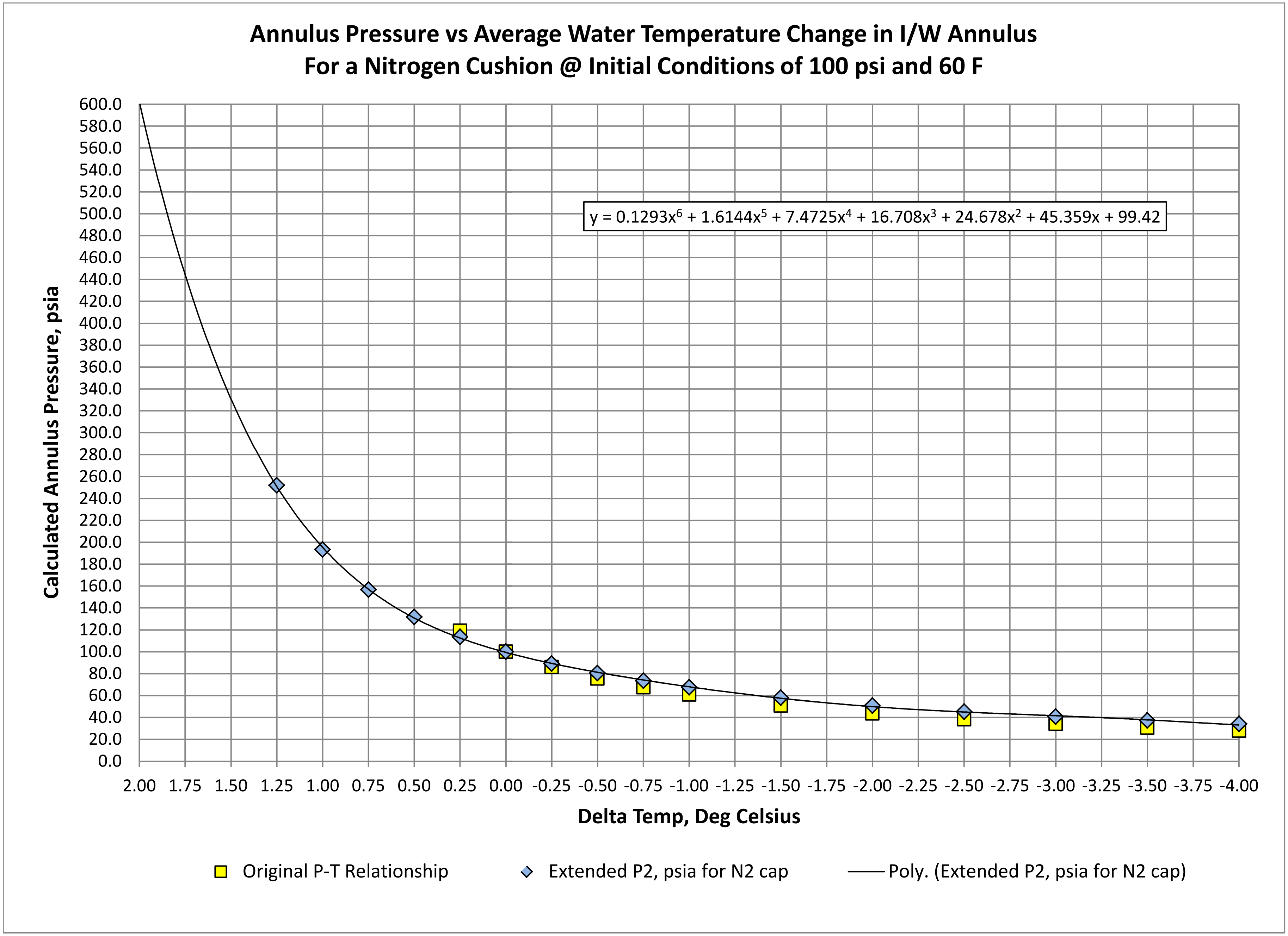
V_{wi} = Initial water volume, m^3

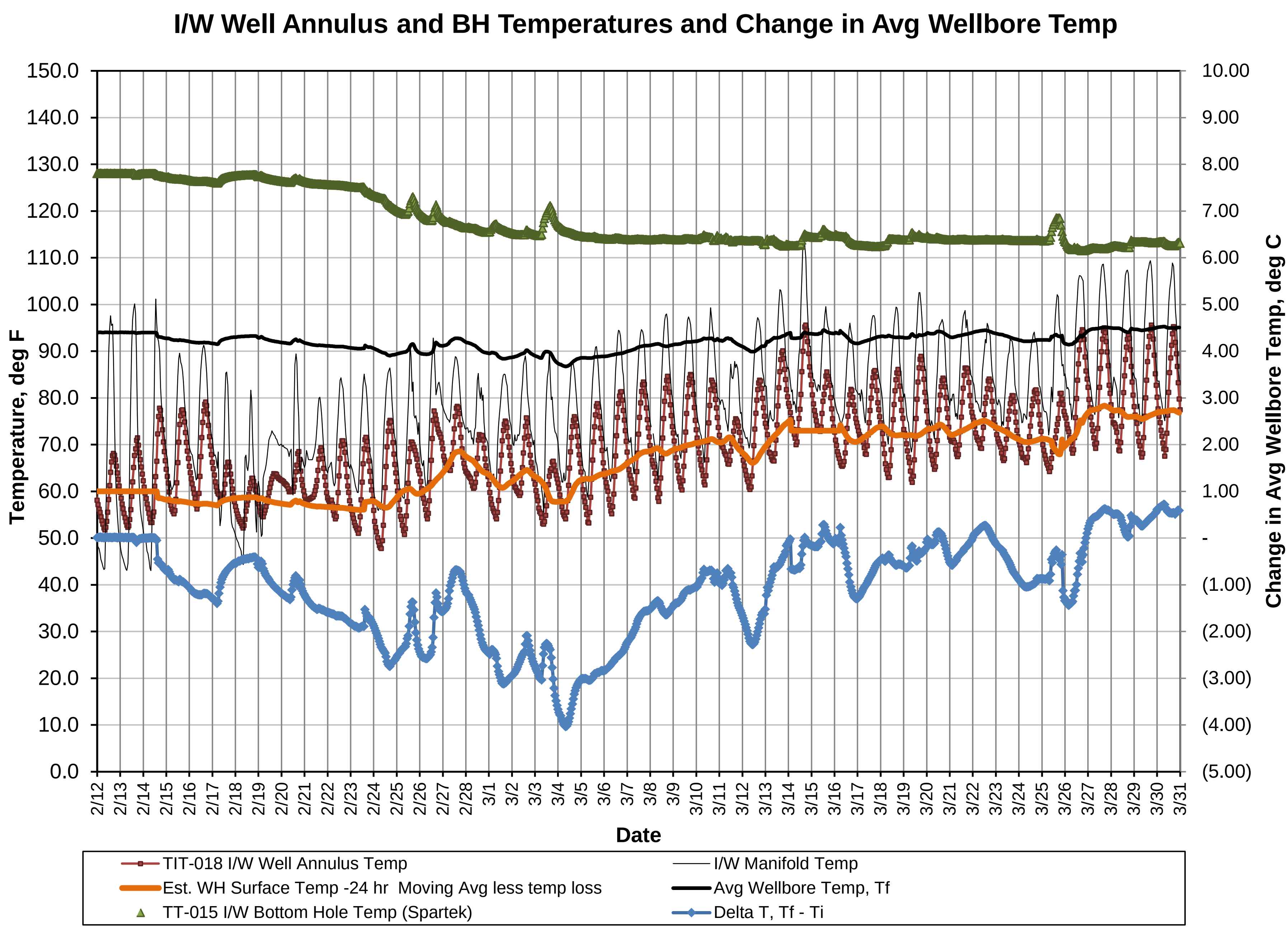
V_{wf} = Final water volume, m^3

Ti = Initial water temperature, ^0C

Tf = Final water temperature, ^0C

β = Volumetric temperature co-efficient of water, $m^3/m^3\ ^0C$


Annulus Pressure vs Average Water Temperature Change in I/W Annulus
For a Nitrogen Cushion @ Initial Conditions of 100 psi and 60 F
y = 0.1293x6 + 1.6144x5 + 7.4725x4 + 16.708x3 + 24.678x2 + 45.359x + 99.42
Calculated Annulus Pressure, psia
600.0
580.0
560.0
540.0
520.0
500.0
480.0
460.0
440.0
420.0
400.0
380.0
360.0
340.0
320.0
300.0
280.0
260.0
240.0
220.0
200.0
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
-0.25
-0.50
-0.75
-1.00
-1.25
-1.50
-1.75
-2.00
-2.25
-2.50
-2.75
-3.00
-3.25
-3.50
-3.75
-4.00
Delta Temp, Deg Celsius
Original P-T Relationship
Extended P2, psia for N2 cap
Poly. (Extended P2, psia for N2 cap)


I/W Well Annulus and BH Temperatures and Change in Avg Wellbore Temp
Temperature, deg F
Change in Avg Wellbore Temp, deg C
Date
150.0
140.0
130.0
120.0
110.0
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
-
(1.00)
(2.00)
(3.00)
(4.00)
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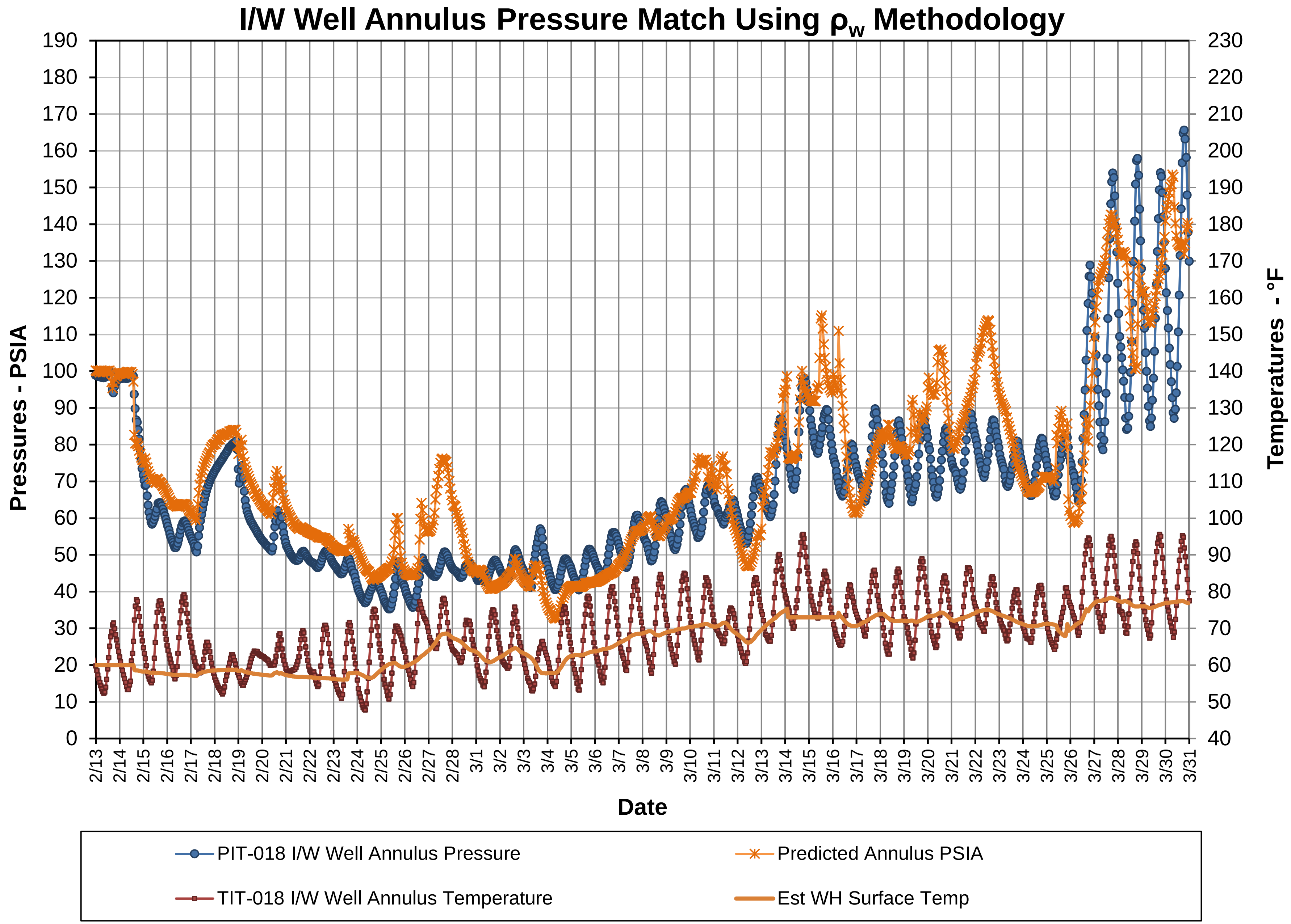
TIT-018 I/W Well Annulus Temp
I/W Manifold Temp
Est. WH Surface Temp -24 hr Moving Avg less temp loss
Avg Wellbore Temp, Tf
TT-015 I/W Bottom Hole Temp (Spartek)
Delta T, Tf - Ti


I/W Well Annulus Pressure Match Using ρw Methodology
Pressures - PSIA
Temperatures - °F
Date
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
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PIT-018 I/W Well Annulus Pressure
Predicted Annulus PSIA
TIT-018 I/W Well Annulus Temperature
Est WH Surface Temp